

**Quarterly Progress Report**

**Technical and Financial**

**Deep Water Ocean Acoustics**  
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## Table of Contents

Notices: .....	1
Table of Contents .....	2
Technical Progress Report .....	3
1. Introduction .....	3
2. Tasks .....	3
a. Task 1: Basin Scale Acoustics and CTBTO Data Analysis .....	3
b. Task 2: NPAL PhilSeal0 Data Analysis and Matched Field Processing.....	8
3. Future Plans .....	12
Financial Progress Report: Period ending June 30, 2015 .....	14

# Technical Progress Report

## 1. Introduction

The goal of this research is to increase our understanding of the impact of the ocean and seafloor environmental variability on deep-water (long-range) ocean acoustic propagation and to develop methodologies for including this in acoustic models. Experimental analysis is combined with model development to isolate specific physics and improve our understanding. During the past few years, the physics effects studied have been three-dimensional propagation on global scales, deep water ambient noise, under-ice scattering, bathymetric diffraction and the application of the ocean acoustic Parabolic Equation to infrasound.

## 2. Tasks

### a. Task 1: Basin Scale Acoustics and CTBTO Data Analysis

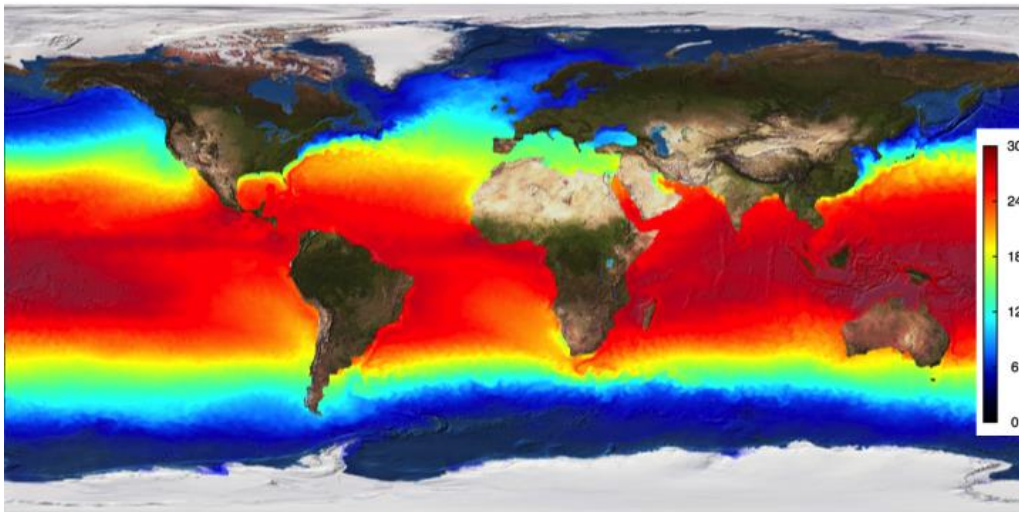
#### *Scenario*

The scenario chosen to evaluate the impact of mesoscale variability on the arrival angle of long-range signals is a seismic event on the Kerguelen Plateau (-53°S 71°E) in the southern ocean. This region of the world, which includes Heard Island, Crozet Island and the Kerguelen Plateau has historical significance in the long-range underwater community (Perth-Bermuda, HIFT) and is the position of the IMS hydro-acoustic station HA04. As demonstrated in the Heard Island Feasibility Test, sound sources here can be detected from the Southern Atlantic to the Pacific. The receiver position is taken to be approximately at the IMS HA10S location (Ascension Island southern station). The hydroacoustic station at Ascension, as can be seen in Figure 1, has acoustic visibility to the South Atlantic, South Indian and South Pacific and has a large number of hydroacoustic signals generated by seismic events.

The Kerguelen-Ascension path was also chosen because of the relative minimal bathymetric variability along the geodesic. For low-frequency acoustic signals, bathymetric variation leads to refraction<sup>1</sup> and diffraction<sup>2</sup> and this complicates the evaluation of the impact of mesoscale variability. Mesoscale variability refracts sound from horizontal gradients, primarily ocean fronts and eddies. This scenario has acoustic energy crossing the Antarctic Circumpolar Convergence, the strong boundary between the Southern Ocean and the Indian Ocean. This path also transects the Agulhas Retroflexion, a dynamic region of eddies that spin off interaction of the Agulhas current with the coast of South Africa<sup>3</sup>. The deflection of acoustic energy due to interaction with these eddies was evaluated by Munk to see if they could explain the Perth-Bermuda results<sup>4</sup>. He found them to be too weak for the geometry of Perth-Bermuda.

The time and range-dependent ocean used for this simulation study is the eddy-resolving ECCO2 (Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2): High-Resolution Global-Ocean and Sea-Ice Data Synthesis) model re-analysis for the years 1992 and 1993. The ECCO2 model is a state estimation based upon data syntheses obtained by least squares fitting of the global ocean and sea-ice configuration of the Massachusetts Institute of Technology general circulation model (MITgcm) to the available satellite and in-situ data<sup>5</sup>. The ECCO2 product is the temperature and salinity vs. depth (50 depth layers) on a  $\frac{1}{4}$  degree grid, produced every 3 days. The sea-surface temperature (SST) for ECCO2 model for January 1, 1992 is shown in Figure 2. Regions of strong mesoscale activity (eddies) are visible off the Northeast coast of the United States (the Gulf Stream) and Japan (the Kuroshio) and south west of South Africa (the Agulhas Retroflection).

## Ecco2 Model (19920105)

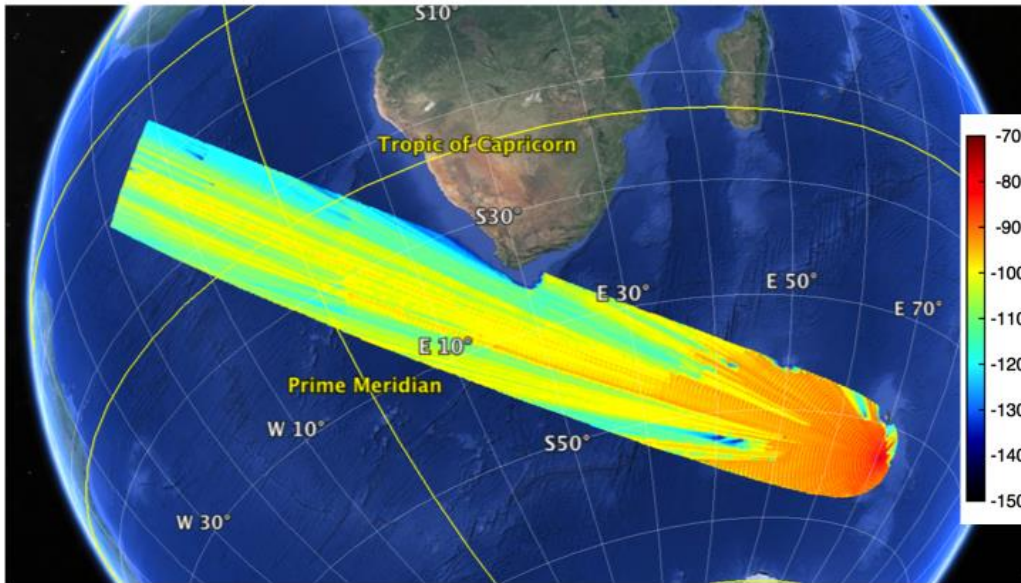


*Figure 2. ECCO2 sea-surface temperature for 19920101.*

### *Modeling approach*

The Peregrine model is used to compute the acoustic field, including out-of-plane propagation with the ECCO2 reanalysis model every 3-days from 1992 to 1993. In order to reduce the computational cost for long-range propagation in Peregrine, the computational grid can be confined to a swath around a geodesic bearing. The center bearing is  $268^\circ$  and the swath width is 1200 km. The source depth is 730m and the maximum range computed is 9100 km. The bathymetry is taken from the ETOPO1 dataset. For the 2Hz computation, where even the deep-water bathymetry did show an impact on the field, a flat seafloor of 3000m depth was imposed to remove this effect. The seafloor is set to be an acoustically deep layer of medium silt (sediment grain-size 6), and is not expected to play a role in this study.

## Kerguelen Plateau to Ascension 3D Propagation



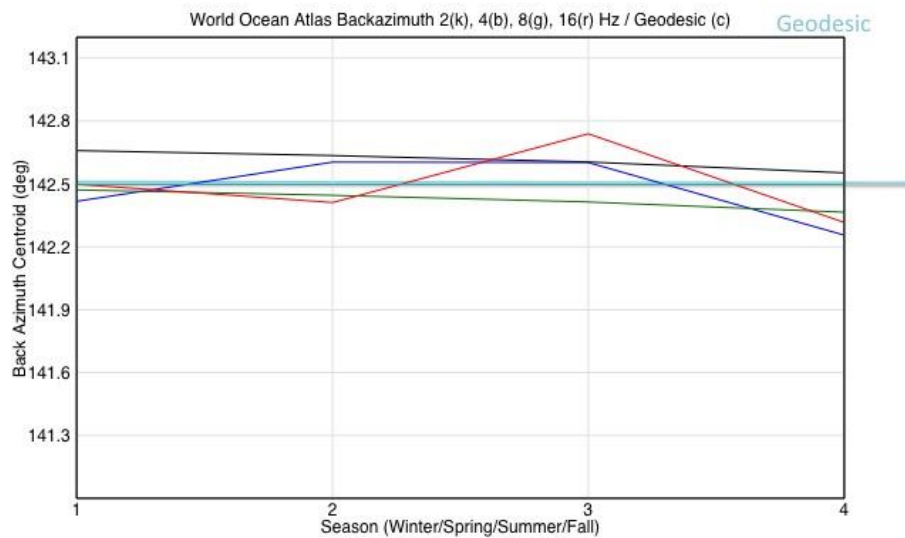
*Figure 3. 8Hz depth averaged Transmission Loss (TL) for Kerguelen source showing propagation tube.*

The depth averaged transmission loss in Figure 3 shows the diffractive filling of the shadows behind Crozet Island and Agulhas shelf, as well as the open water path from Kerguelen to Ascension (the center of the final range swath). The field was computed with 4 points per wavelength in the horizontal and 4 Pade terms in the Split-Step Pade<sup>6</sup> expansion in the horizontal. The field was computed every 3 days for 2, 4 and 8 Hz and every month for 16 Hz.

In order to estimate the back-azimuth, a 2D planar array centered at 8° 53' S and 14° 37' 30" W was used. The complex pressure field was computed on a 360 x 312 grid with spacings of 30.9m and 35.6m for longitude and latitude, respectively. The receiver depth was 834m, the reported depth of HA10S. Narrow band plane wave beamforming, with Hann window shading, was performed on each arrival. The geodesic back-azimuth, using the WGS'84 globe, between the source and array center is 142.498°. For all frequencies computed, the array spacing is greater than a quarter-wavelength, but grating lobes are handled by only beamforming around the expected azimuth of the acoustic energy.

## Results

Prior to evaluating the mesoscale refraction of the eddy-resolving ECCO2 model, the refraction induced by large-scale oceanographic features, such as crossing the Antarctic Circumpolar Front is examined. The World Ocean Atlas 2009<sup>7</sup> temperature and salinity fields for the four seasons was used. The results, for 2, 4, 8 and 16 Hz, are plotted in Figure 4, along with the geodesic (in cyan). There is very little seasonal dependence observed and all of the back-azimuths are within 0.25° of the geodesic. This minimal deviation from the geodesic may result from the inherent smoothing of gradients when computing a climatology database.



*Figure 4. Centroid of beamformed arrival vs season using the World Ocean Atlas for each season (Winter, Spring, Summer and Fall). The frequencies computed are 2Hz (black), 4Hz (blue), 8Hz (green) and 16 Hz (red). The un-refracted geodesic is the thick line in cyan and 142.498°.*

The acoustic field for 2, 4 and 8 Hz was run through the ECCO2 model from January 3, 1992 through December 28, 1993, sampled in three day increments, yielding a total of 243 sample time series. Due to the frequency-cubed cost of the 3D PE computation, the 16 Hz runs were computed monthly for the same time period. The beam time-series, at the output of the beamformer for the 4Hz signal over the back-azimuths from 135 to 150° is shown in Figure 4. The received beam energy is generally unimodal, with a smooth distribution around a center beam, varies in arrival angle and is dynamic in level. The dynamic range of the plot is 30 dB.

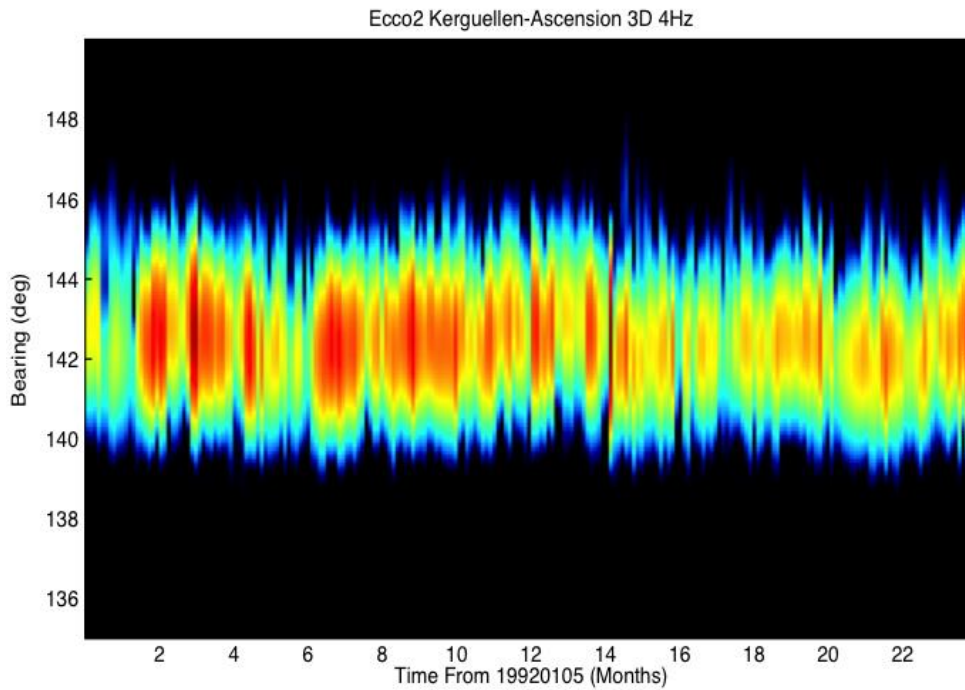


Figure 5. Beam response for 4Hz propagation over the 1992-1993 Ecco2 model.

The beamformer output was collapsed to a single back-azimuth value by computing the centroid of the beam power over the searched arrival angle. The time-series of the back-azimuth for the set of model simulations is shown Figure 6, along with the geodesic back-azimuth. This simulation is not finished to the point of being publishable. There is substantially more refraction observed in the ECCO2 result than in the WOA09 result, indicating the combined impact of the mesoscale eddies and sharper front definition is important to the acoustic propagation path. There is a long time-scale oscillation on the order of a 120-day period, ostensibly related to seasons, but it does not repeat for each season of 1992 to the corresponding season of 1993. This oscillation leads to the range in the back-azimuths going from a minimum near  $141.5^\circ$  to a maximum of  $143.1^\circ$ . The back-azimuth as a function of frequency does show coherent behavior, at least within the observed  $0.3^\circ$  small time scale variability. There is a consistent 3-6 day oscillation with a peak magnitude of  $0.3^\circ$  in the 4 and 8Hz data which could be random noise, or could be due to small scale motions of the eddies and the bathymetry. Note the 2Hz signal does not have this oscillation. Recall that it was computed using a flat seafloor to remove dominant bathymetry effects.

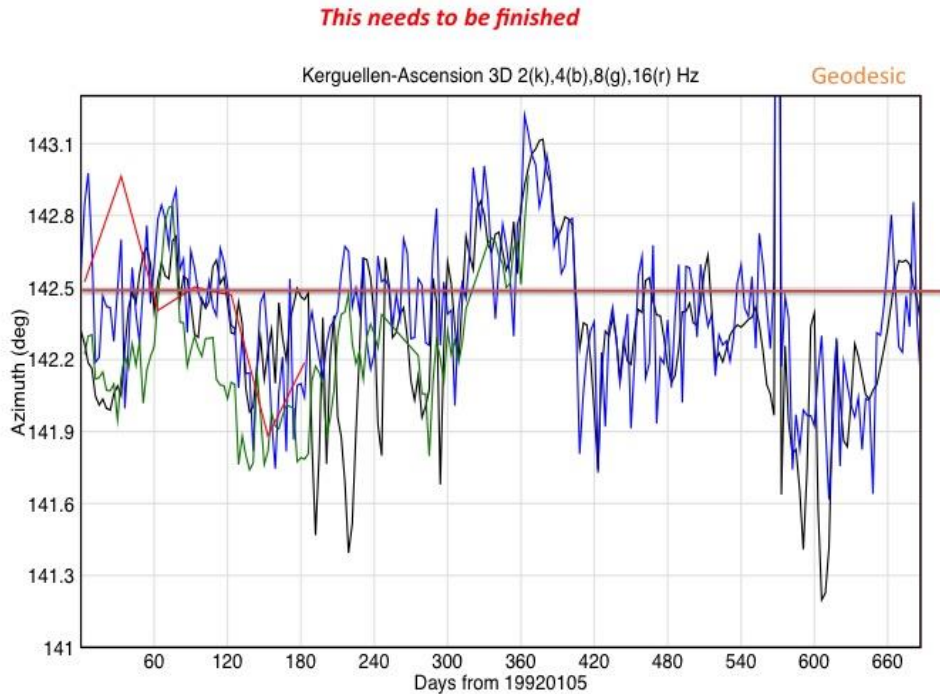


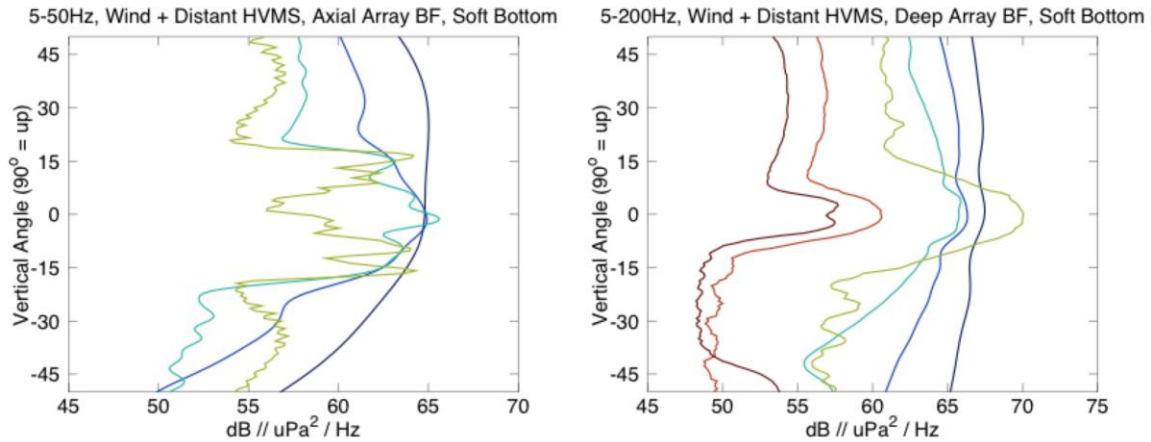
Figure 6. Centroid of arrival energy for 2-16 Hz over 1992-1993 Ecco2 model.

#### b. Task 2: NPAL PhilSeal0 Data Analysis and Matched Field Processing

PhilSea09 analysis involved noise modeling and analysis of the vertical directivity from the PS09 Vertical Line Array. PS09 was chosen because this VLA was spaced at  $\lambda/2$  at 250Hz and is therefore beamforming capable, covering the conjugate depth.

An ambient noise model was built for predicting the vertical noise component of the ambient noise. The model used Peregrine for hydrophone to  $\lambda/4$  depth below the surface (for a noise sheet and for ships) to the edge of the Philippine Sea basin. Wind speed was computed by adding each surface patch to the array cross-spectral density (corresponding to the Kuperman-Ingenito surface sheet of independent sources). Shipping was input via a realization of the HITS model for the Philippine Sea. The results are dependent upon the seafloor. For a soft sediment, the modeled vertical noise directivity at the axis and at the conjugate depth are shown in Figure 7.

## Beam Noise on Axial and Deep Subarrays: Soft Bottom



- Nearby shipping not included
- No noise notch below conjugate region
- Moderate noise notch at higher freqs at axis

*Figure 7. Vertical Noise Directivity as a function of frequency for an axial (left) and deep (right) vertical line array for frequencies from 5-50Hz (axial array) and 5-200Hz. – Which are the unaliased beamforming capable frequencies of the deployed arrays.*

We now compare the deep VLA noise vertical directivity of the measurement from those modeled using a hard seafloor and a soft seafloor. The result is shown in Figure 8, indicating the seafloor is best modeled as hard.

# Model/Data Comparison: Beams

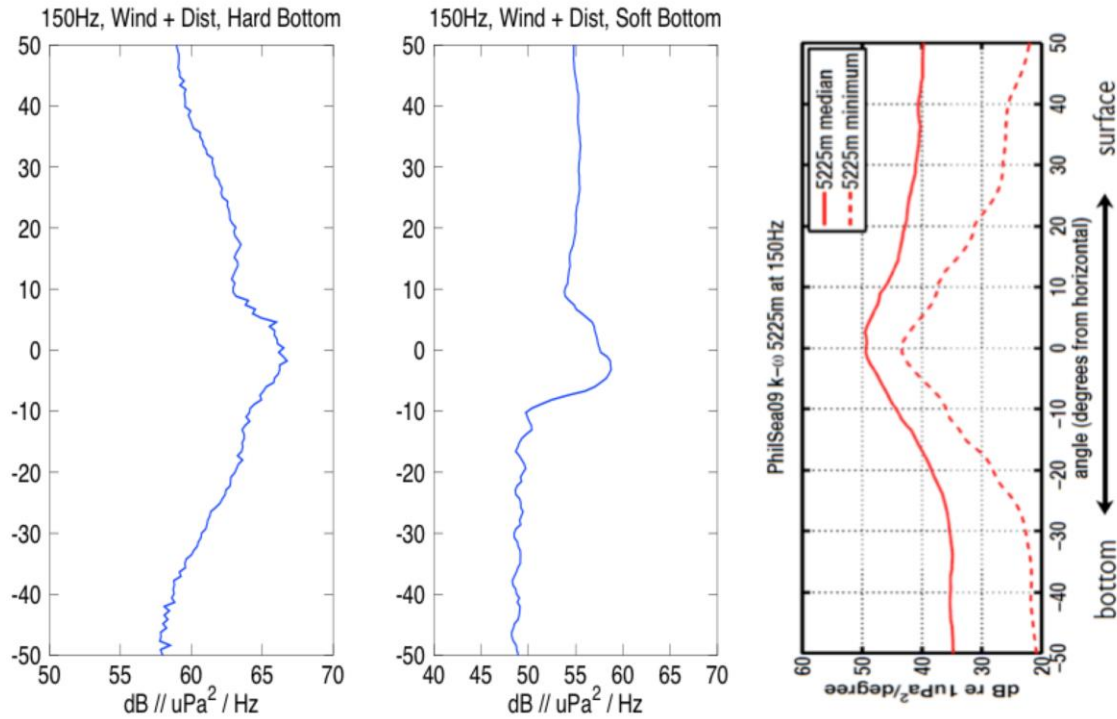
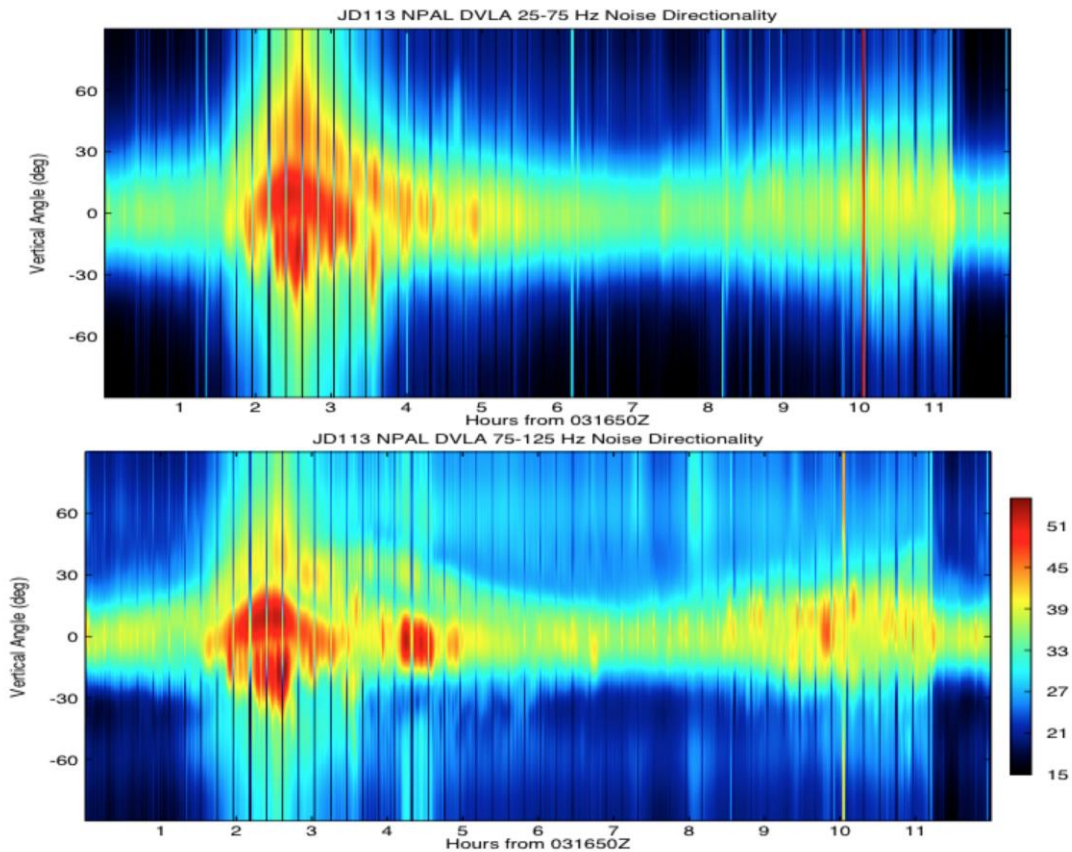


Figure 8. Vertical Noise Directivity for 150Hz using a hard seafloor (left), soft (middle) and from the observations. The lack of a clear critical angle indicates a harder sediment.

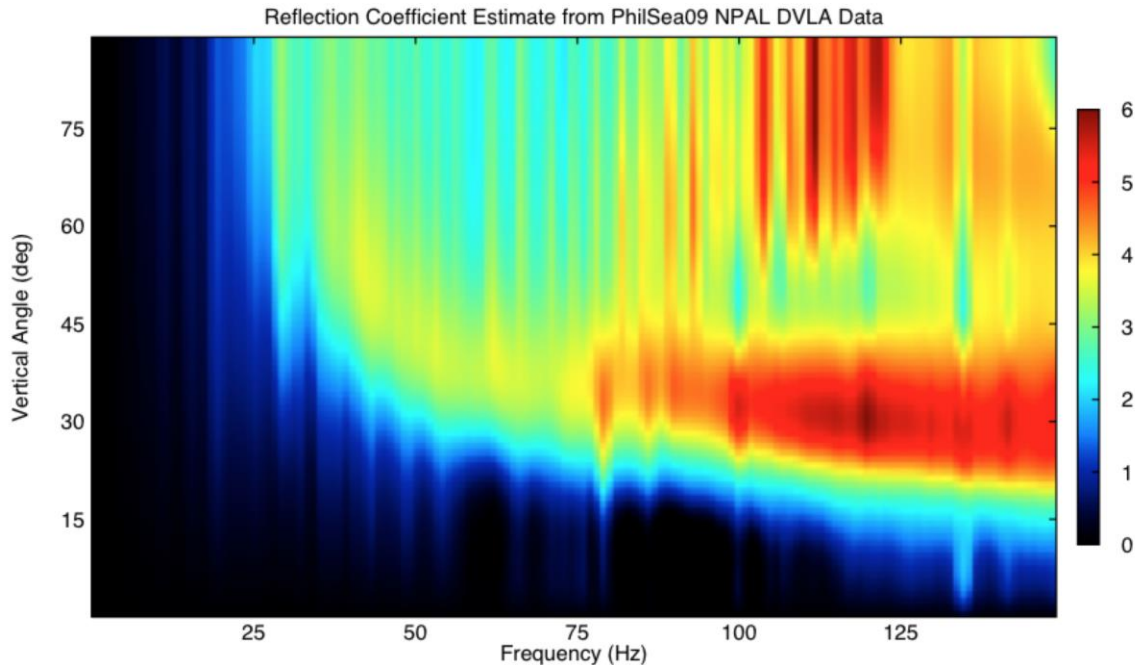
The deep VLA data was processed for 24 hours. The band averaged, Hann-windowed BTR (Bearing Time Record) of vertical angle vs. time is shown in Figure 8.



*Figure 9. Bearing Time Records for 25-75 Hz and 75-125Hz for the DVLA on Julian Day 113. The CPA of the R/V Revelle is seen at hour 2:30.*

The CPA of the surface ship is evident at hour 2, with the associated high angle energy, particularly at low frequency. Note the energy, particularly in the upper band during the quiet periods that is coming in from the above the array (positive vertical angles). This is wind energy from above. It is not evidently coming from below, a physical phenomenon Harrison attributed to the bottom energy having 1 more bottom bounce. This leads to the technique of estimating the reflection coefficient by subtracting the downward energy from the upward energy (for each corresponding beam). The result of this operation is the estimated reflection coefficient vs. frequency and is shown in Figure 10.

# Ambient Noise based Reflection Coefficient Estimation



*Figure 10. Estimated reflection coefficient as a function of frequency by taking the difference of downgoing and upgoing energy.*

### 3. Future Plans

For the next quarter, the focus of the work will be on examining measurements and models of the 3-dimensional diffraction induced by bathymetric scattering. Observations have been made from the CTBTO hydroacoustic stations of seismic events that are in the acoustic shadow due to island (or continent) blockage. The 3D Peregrine model will be applied to these examples demonstrating that diffraction can explain the observations of hydroacoustic signals in the deep shadow.

Theoretical work, following Munk's approach, will be done to compute the expected energy observed due to diffraction from an edge.

The impact of bathymetric diffraction on the global coverage of the CTBTO network will be evaluated. Early computations indicate that the filling in from bathymetric diffraction can be on the order of 3% of the earth's globe, for a single station, which corresponds to 15 million km<sup>2</sup>.

## 4. Publications and Peer Interactions

Dr. Heaney presented at the ASA in Pittsburgh and at the Conference on Ocean Noise in Sevilla, Spain. He met with Dr. Laslo Evers (KNMI) and Dr. Michael Ainsle, during a visit to the Netherlands. Dr. Heaney visited the CTBTO (Vienna) and met with Dr. Mario Zampolli. He wrote a conference paper and presented on global acoustic propagation (including on Europa, a small moon of Jupiter) at the International Conference of Sound and Vibration (ICSV) in Florence, Italy.

Dr. Heaney has written a Mesoscale Refraction paper for JASA and it will be submitted in the next few weeks.

## 5. References

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## Financial Progress Report: Period ending June 30, 2015

OASIS, INC.

JOB STATUS REPORT

6/30/2015

1172 DEEP WATER ACOUSTICS

N00014-114-C-0172

POP: 9/27/13-3/6/16

<u>CONTRACT VALUE</u>	Cost	Fee	Total
Contract Value	\$368,935	\$27,048	\$395,983
<b>Funding Value:</b>	<b>\$215,404</b>	<b>\$15,791</b>	<b>\$231,195</b>
Remaining to Fund:	\$153,531	\$11,257	\$164,788

### CUMULATIVE SPENDING WITH COMMITMENTS

	DIRECT	OH	MH	TOTL COST	FEE	TOTAL
<b>ACTUAL</b>						
OASIS	\$84,368	\$62,700	\$1,842.00	\$148,910	\$11,168	<b>\$160,078</b>
<b>COMMITTED</b>						
	\$0	\$0	\$0	\$0	\$0	<b>\$0</b>
	\$84,368	\$62,700	\$1,842	\$148,910	\$11,168	<b>\$160,078</b>
<b>TOTAL REMAINING TO SPEND:</b>						<b>\$71,117</b>